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by R. M. W. Frederking

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Ice action on Nanisivik wharf, Strathcona Sound, N.W.T., winter 1978-1979

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Field observations have been made over three winters at a vertically faced wharf in an area of limited horizontal ice movement but substantial vertical movement due to tides. Ice thickness was profiled and vertical ice movements were measured. A reasonably consistent pattern of ice behaviour adjacent to the wharf was established, characterized by the formation of a transition ice zone between the first-year sea ice and the wharf. The behaviour and factors affecting growth of this zone are described.

Des observations sur place ont été faites pendant trois hivers sur un quai vertical dans une région où le mouvement horizontal de la glace est limité, mais à mouvement vertical substantiel causé par les marées. L'épaisseur de la glace a été profilée et les mouvements verticaux de la glace mesurés. Une courbe assez uniforme du comportement de la glace près du quai a pu être relevée se caractérisant par la formation d'une zone de glace en transition entre la glace d'eau de mer d'une année et le quai. Le comportement et les facteurs qui influence la croissance dans cette zone sont décrits.

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Introduction

As a continuation of a long-term Division of Building Research - National Research Council of Canada program of investigations of the performance of structures subjected to ice action, observations have been made at the Nanisivik Marine Terminal, Strathcona Sound, N.W.T. The results of a previous investigation at the site have been presented earlier by Frederking and Sinha (1978). This note contains the results of observations and measurements of ice behaviour during the winter of 1978-1979 and presents certain conclusions drawn from them.

Site Description

Strathcona Sound is located off Admiralty Inlet on the northern end of Baffin Island. The wharf site is on the south shore of the sound, about 20 km from its outlet.

The wharf structure consists of three sheet-piled gravel-filled cells about 75 m offshore. At the outer edge the minimum water depth is 13.5 m. The cells are connected by a rock-filled apron joined to the shore via a causeway (Fig. 1).

The sound is generally covered by a smooth sheet of ice that has, on average, a maximum thickness of 1.6 m. There is no apparent horizontal movement of

FIG. 1. Hinge and crack pattern around wharf, March 1979.

the ice cover, but the maximum tidal range is about 2.5 m. Freeze-up generally occurs in late September.

General Ice Conditions for Winter 1978–1979

The first stable ice cover formed on the sound during mid-September, and by 15 October the ice thickness was over 0.25 m. Two ships called at the wharf in the autumn, the *Gothic Wasa* from 30 September to 3 October and the *M.V. Arctic* from 10 to 14 October. The broken track left by the vessels was still visible in March 1979. At the end of September the ice adjacent to the wharf was reported to be about 15 cm thick. A maximum thickness of 26 cm was measured on broken upturned ice pieces left in the wake of the last ship. This thickness would pre-

sumably correspond to the mid-October departure of the *M.V. Arctic*. It was reported that ice prevented the ships from being moored immediately adjacent to the wharf. Both ships are ice-going bulk carriers with a long parallel-wall-sided midbody section.

Ice Behaviour around Wharf

Detailed measurements and observations of ice behaviour were made during a site visit at the end of March 1979. Additional supplementary information was obtained from periodic observations carried out during the winter.

Cracks and Hinge Pattern around Wharf

Previous observations at the site established that because of tidal action a network of hinges and cracks formed to accommodate the differential vertical movement between the ice cover and the wharf. Hinges are defined as features across which relative rotations of several degrees or more occur, whereas cracks involve relative rotations of less than one degree. The actual pattern of this network is shown schematically in Fig. 1. The area designated as the "active zone" is the transition from the fixed ice foot and wharf, and the free floating ice cover. Because of the larger rotations at the hinges, it was possible for water to flood up into the intervening space and freeze. An overview of the ice around the wharf is shown in the composite photograph in Fig. 2.

Ice Profile

The ice cover was profiled along a line running out from the centre cell (Fig. 1). This was accomplished by drilling through the ice cover to measure its thick-

FIG. 2. Composite photograph showing ice features adjacent to wharf, 23 March 1979, 11:15 h.

FIG. 3. Ice profiles at high and low tides, 25 March 1979. (a) High tide (10:05 h). (b) Low tide (16:35 h).

ness as well as running level surveys to establish the elevations of the ice surface. Profiles at high tide (10:05) and low tide (16:35) 25 March 1979 are shown in Fig. 3; note that the vertical and horizontal scales are equal. From Fig. 3a it can be seen that at high tide the high water level (HWL) is above the ice surface of the active zone. It was observed that at high tide seawater flowed up between the active zone and the cell, flooding the surface. The resulting pond froze (Fig. 4), forming a layer of ice about 20 mm thick superposed on the existing ice as the water level decreased with the falling tide. At low tide (Fig. 3b), the low water level (LWL) is above the ice surface at the outer edge of the active zone. Again flooding was observed and a similar process of ice formation occurred. This process resulted in a rapid buildup of ice. The measured ice thickness in the active zone was about 5 m, whereas the average thickness of the first-year sea ice was about 1.4 m. It was noted that the natural ice cover curved upwards at the point where it interacted with the active zone. This suggests that a net vertical upward force is transmitted from the active zone, through the hinge, to the first-year sea ice.

Rotations and Deflections in Active Zone

In addition to the level survey measurements, vertical stakes were frozen into the ice 2, 8, 10, and 30 m from the wharf along an axis extending out from the centre cell. Actual locations are indicated

by the designations T2, T8, T10, and T30 in Fig. 3a. The inclination angles of these stakes were measured periodically with an improvised tiltmeter. The results of the first set of slope measurements made 24 March 1979, during a period of falling tide, are presented in Fig. 5. A positive value for ice surface slope indicates that the surface inclines down towards the wharf. The precision of these measurements was $\pm 0.2^\circ$. The two stakes on the active zone, T2 and T8, show the same slope variations with time, which confirms that the active zone rotates as one piece adjacent to the centre cell. The stake T10 on the curled up portion of the natural first-year sea ice indicated measurable slope changes. The direction of the slope changes at this location appears to be opposite to that in the active zone. The slope changes measured at T30 fall within the range of measurement error, so it was assumed that there were no rotations there. Checks made at T30 on subsequent days confirmed this assumption. A further set of tilt measurements was made 25 March 1979 (Fig. 6). In this case tidal elevations were measured by means of level surveys to a bench mark at T30. It can be seen that the rotation of the active zone, from tiltmeters T2 and T8, was in unison with the tide. From high tide to low tide the total rotation was about 6.5° . The level survey results in Fig. 3 indicated a similar rotation plus a vertical translation of about 0.8 m at the wharf side of the active zone. The corresponding tide range was about 1.7 m. This indicates that the active zone

FIG. 4. Freshly frozen surface of pool formed at high tide, 24 March 1979, 09:45 h.

FIG. 5. Variation of ice surface slope angles, 24 March 1979.

both rotates and translates vertically with respect to the outer edge of the centre cell. On-site observations showed the translation to be of an intermittent nature for both rising and falling tides. Again the rotations at T10 were in the opposite direction to those of the active zone and had a range of about 1° .

Growth of the Active Zone

The ice adjacent to the wharf was photographed several times during the 1978–1979 winter. From the photographs the width of the active zone adjacent to the centre cell was estimated. Width estimates are plotted in Fig. 7. Also shown on this figure is the width increase observed during the 1975–1976 winter

FIG. 6. Variation of ice surface slope angles, 25 March 1979.

at the west cell. It is clear that there was a progressive increase in the width of the active zone throughout the winter.

Discussion of Results

Detailed observations during the winters of 1975–1976 (Frederking and Sinha 1978) and 1978–1979, as well as qualitative observations during the winter of 1977–1978 (R. Goodbody, personal communication, 1978), indicate that the ice behaviour reported

FIG. 7. Lateral expansion of active zone.

in this paper is typical for the site. A series of hinges and cracks accommodating the relative movement between the floating first-year sea ice and the wharf is formed in the same systematic pattern each winter (Fig. 1).

As part of this ice accommodation to the tides a peculiar ice feature, called the active zone, forms between the first-year sea ice and the wharf. The growth of the active zone is two dimensional. Surface flooding at high tide, shown in Fig. 4, results in the formation of a layer of ice each tidal cycle. Confirmation of this vertical growth was found in the thickness measurements.

The mechanism for the horizontal growth is not clear, but it would appear to be related to ice buildup on the vertical face of the active zone adjacent to the wharf. The actual increase in width of the active zone is about 1 m/month (Fig. 7).

As was reported in an earlier report (Frederking and Sinha 1978) the increase in width of the active zone occurred concurrently with an equivalent movement of the edge of the first-year sea ice away from the wharf. In the 8 month period from October to June, the edge moved about 10.5 m (Fig. 7). The width of the sound at this location is about 5500 m. Assuming that the movement of the edge was absorbed uniformly by deformation in the ice cover, the total strain averaged across the width of the sound would be about $1900 \mu\text{m}/\text{m}$. Alternatively, it could be assumed that the active zone acts like an indenter against the ice cover, in which case the strain in the ice adjacent to the active zone would be even higher. Because the actual strain distribution for indentation of a nonlinear material like ice is complex to define, the case of uniform deformation will be assumed for the following calculation, even though it describes a less severe condition. Averaged evenly over an 8 month period this would correspond

to a strain rate of about 10^{-10} s^{-1} . Using a constitutive equation developed by Sinha (1978) it is possible to calculate the constant stress that would cause ice to deform at the above rate. For an ice temperature of -20°C this stress would be about 150 kPa.

The foregoing arguments in regard to ice strain and stress have been qualitative, but they have provided a basis for making an order of magnitude estimate of the average stress in the ice cover. The transmission of this stress through the active zone to the wharf is obviously complex. No attempt has yet been made to estimate the ice pressure it might impose on the wharf.

Examination of the active zone motion as shown in Figs. 3, 5, and 6, and its horizontal extent as presented in Fig. 1, suggests that the active zone, at least adjacent to the centre cell, rotates on an axis running through the hinge at the ice foot. This would explain the relative vertical movement between the active zone and the wharf observed in Fig. 3. It would be reasonable to assume that normal and frictional forces are developed on the contact surface between the active zone and the wharf. The mechanism by which horizontal and corresponding vertical frictional forces are developed is postulated to be tidal jacking of the active zone. With each falling tide a thin layer of ice is formed on the vertical face of the active zone adjacent to the wharf. Then, with the rising tide, the slightly wider active zone jams between the wharf and the first-year sea ice developing horizontal forces. Buoyant forces generated by the tide are the primary driving force for the process.

Buoyant forces may also play a secondary role in that the active zone is not always in hydrostatic equilibrium. At high tide (Fig. 3a) it appears that there would be a net vertical upward force on the outer edge of the active zone due to buoyancy. This would produce a vertical upward force on the curled up edge of the first-year sea ice. Support for this is found in the tilt measurements at T10 (Figs. 5, 6), which showed a steeper slope angle at high tide (-13°) than at low tide (-12°).

The existence of the active zone, which extends the full length of the wharf, has serious implications to winter use of the wharf by ships. The width of the active zone would prevent direct access to the wharf. Being about three times as thick as the natural sea ice, the active zone has greater resistance to breaking. Employing an icebreaker in such close proximity to the wharf would be difficult and hazardous for the vessel and could also damage the wharf. When winter navigation is contemplated at such wharf facilities,

consideration would have to be given to the special circumstances caused by the formation of an active zone.

Further field investigations are being planned to improve the understanding of the processes involved in ice behaviour adjacent to the wharf. That research will take the form of: (1) observations on the increase in width with time of the active zone to better define the growth process; (2) measurements of the physical properties of the active zone, such as density, temperature, and salinity to aid in estimating buoyancy forces; and (3) observations of ice behaviour on the shore adjacent to the wharf for comparative purposes. Previous attempts to measure ice forces at the wharf were not successful. Renewal efforts, however, will be directed to the development of transducers to measure *in situ* ice stresses in the active zone and the first-year sea ice, as well as transducers to measure ice forces on the wharf.

Conclusions

Ice conditions have been observed adjacent to a sheet pile cell wharf in an area of limited horizontal movement, but of substantial vertical movement caused by tides. It has been established that the movements described are typical for the location.

The conditions are characterized by the formation of a large ice feature, termed the active zone, immediately adjacent to the wharf. A mechanism for the generation of ice force on the wharf, based on tidal action on the active zone, has been postulated. Further observations and measurements will be required, however, before a quantitative model for ice forces can be developed. The existence of the active zone has implications for winter navigation at the wharf.

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